Maximizing Physical Layer Capacity for LEO Satellites

Ad hoc strategies and technologies triple the download by exploiting available link resources and conditions.

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Outline

- *Leo path dynamics*
- *Traditional link design methodology*
- *Data quantity per pass*
- *Benchmark capacity definition*
- *Capacity upper bound*
- *Variable data rate concept of operations (CONOPS) and performance*
- *Download capacity comparison*
- *Supportive technology*
- *Review*

Variable Data Rate CONOPS Increases Download Capacity over a Fixed Rate CONOPS

- *Use fixed symbol rate (Rs) to occupy BW allocation*
- *Estimate real-time C/No*
- *Transmit supportable m-ary QAM (with FEC), where m is varied over the pass ($Rc = R_s * Log_2(m)$)*
  - *Incrementally variable data rate is a good approximation of a continuously variable data rate*
  - *Command rate changes from SGT*
  - *Imbed rate change control and sync words in transmission*
- *Adapt and synchronize receiver symbol decision mechanism for changes in m*
- *Calculate capacity per pass as system figure of merit*

Traditional Benchmark Link Design

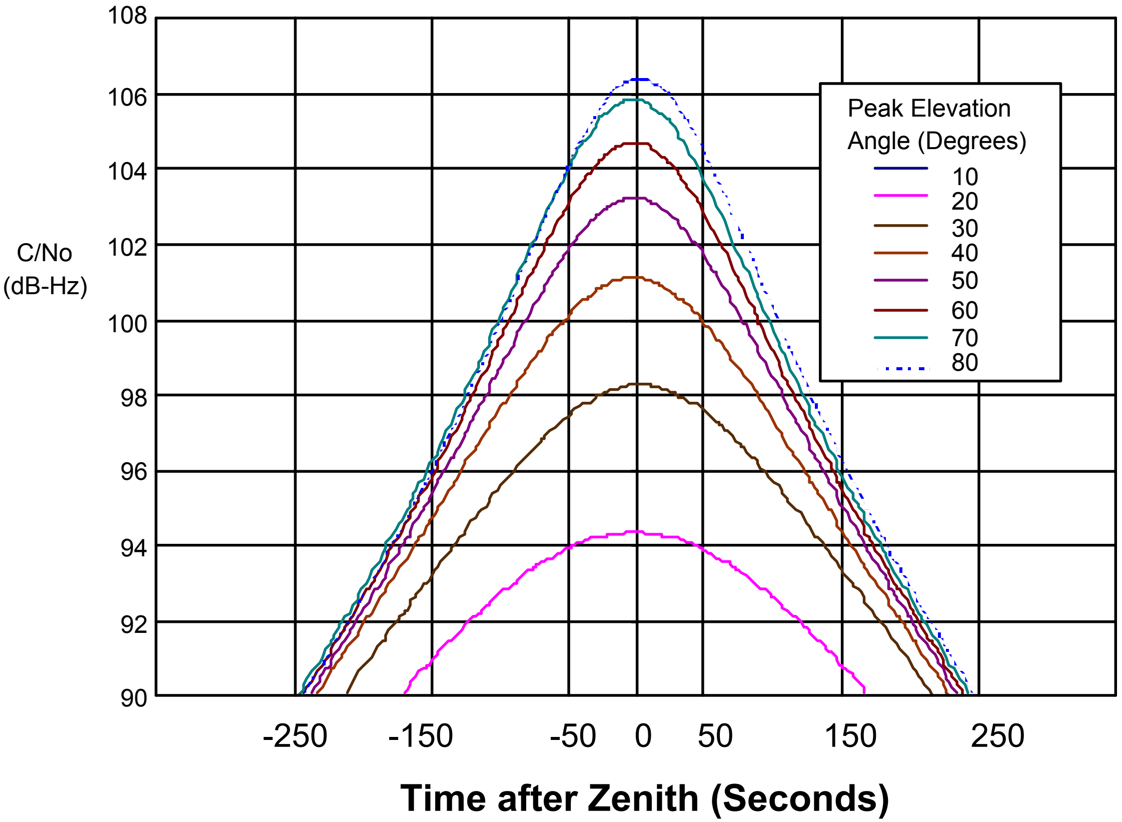
Term	Parameter	Units	Parameter	Units
Transmitter Average Power	20	Watts	13.00	dBW
Nadir Antenna Gain			25.00	dBi
Scan Angle from Nadir	60	Degrees		
Scan Loss			6.00	dB
EIRP				
Transmission Frequency	25	GHz		
Path Length	1000	Nmi		
Free Space Loss			185.62	dB
Minimum Elevation Angle	20	Degrees		
Rain Loss			8.00	dB
Receive Antenna Diameter	1.8	Meters		
Receive Antenna Aperture Efficiency	60	%	-2.22	dB
Receive Antenna Gain			53.24	
Flux Density			-161.62	dBWi
Sky Noise Temperature (in rain)	250	K		
Receiver Noise Temperature	300	K		
System Noise Temperature	550	K	-201.20	dBK
Pointing Loss			0.20	dB
Received C/No			94.84	dB
Allocated Transmission Bandwidth	500	MHz	97.00	dBHz
Receiver Performance Impairment			3.00	dB
Theoretical Eb/No (QPSK w/TPC)			3.00	dB
Supportable Data Rate	88.84	dB-Hz	7.65E+08	BPS
Supportable Data Rate			765.37	MBPS

- ***Fixed data rate, e.g., 622 Mbps***
- ***C/No > 93 dB-Hz***
- ***Large fixed rain margin***
- ***Fixed rain loss margin***
- ***No increased data rate when path parameters improve***
- ***Total download, e.g., a 400-second pass = 249 Gbits***

Based on polar LEO model of Buddinger, et al, "Direct Data Distribution from Low Earth Orbit"

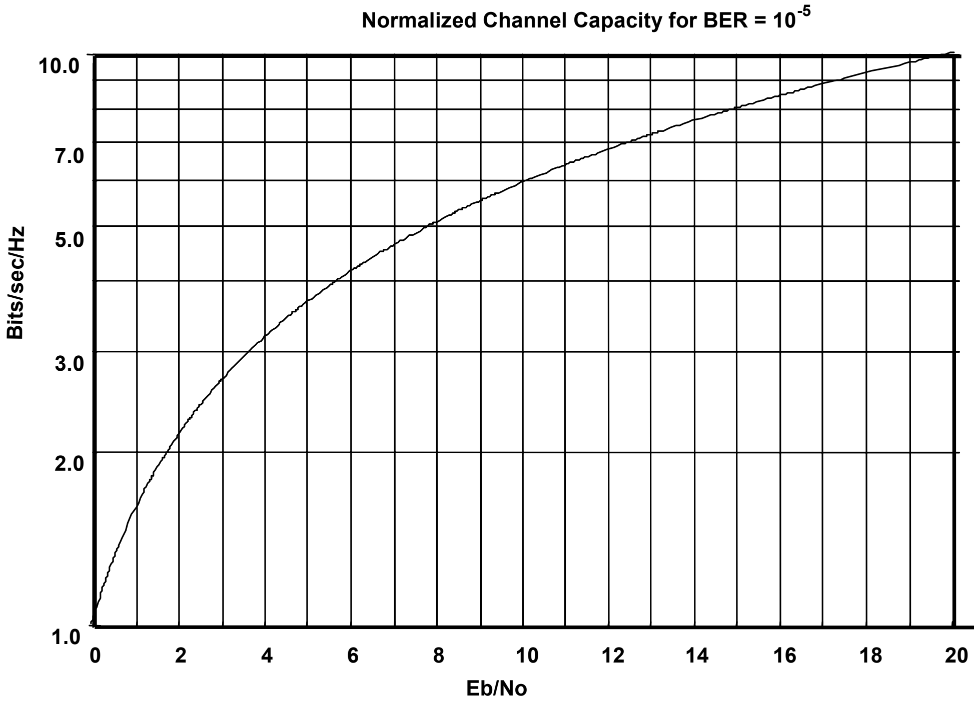
Exemplary System Link Analysis

- ***SNR is variable over all of the pass***
- ***SNR is typically lowest at rise and set***
  - ***Longest path***
  - ***Most atmosphere in signal path***
  - ***Higher rain loss and depolarization***



Capacity Figure of Merit

- ***Total download per pass***
- ***All links are sized for a BER of 10^{-9} or better with FEC***
- ***All cases are compared to Shannon bound, where:***
  Channel Capacity = $W \cdot \log_2(1+C/No \cdot 1/W)$
- ***BW axiom: Lowest W minimizes Eb/No***

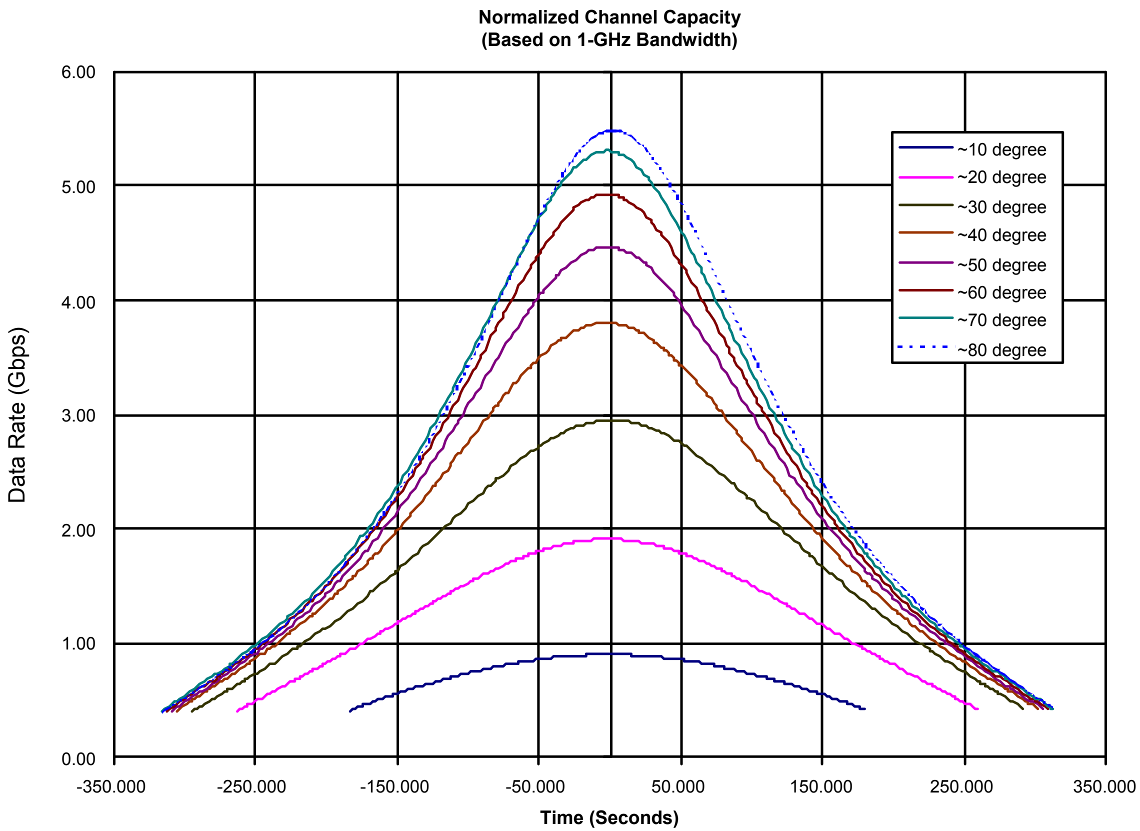


Download Capacity Estimation

- *Determination of "benchmark" performance*
- *Ephemeris and path analysis*
- *Derivation of upper bound of download capacity*
- *Analysis of* ad hoc *incrementally variable data rate*
  - *Free space path loss estimated from known orbital model*
  - *Atmospheric absorption estimate*
    - *Early measurement of SNR at rise*

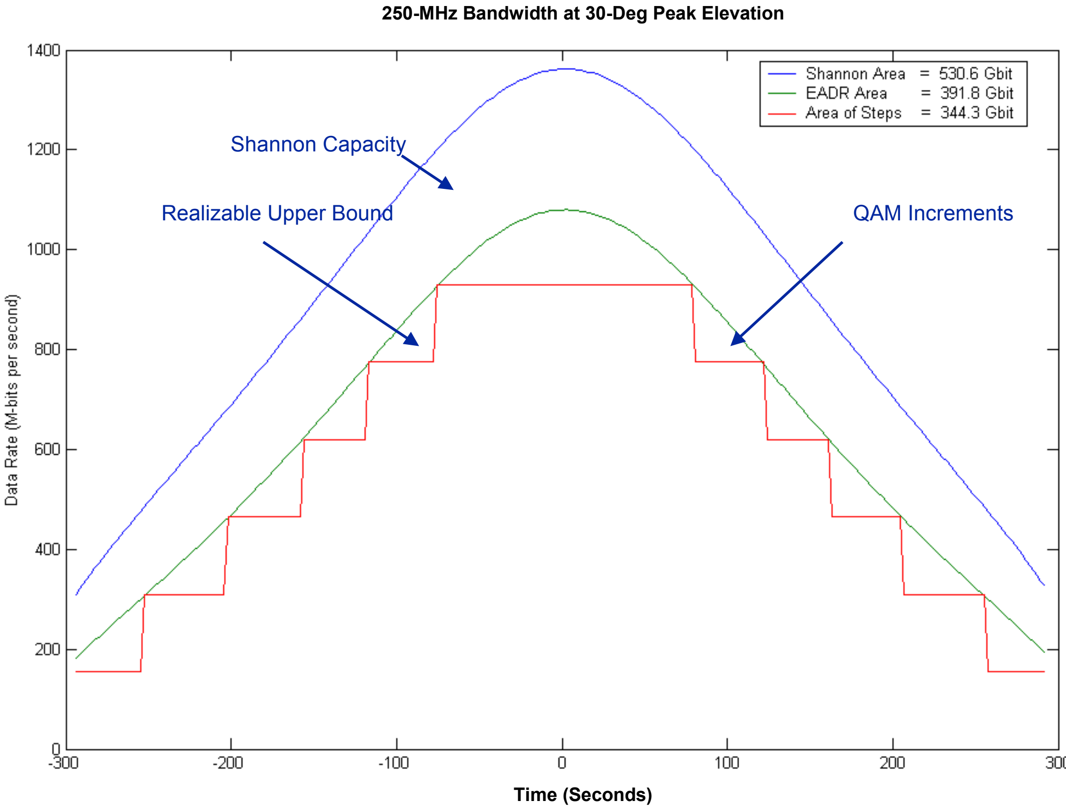
Upper Bound on Available Data Rate

- ***Example given is for 1-GHz passband***
- ***Capacity calculation is based on Shannon bound***
- ***Supportable data rate is highly variable***
- ***Bandwidth limits data rate with practical QAM waveforms***



Integer Multiples of Base Rate Determined by Allocated BW

- *Three BWs and base data rates are chosen as examples*
  - *155 Mbps for 250 MHz*
  - *311 Mbps for 500 MHz*
  - *622 Mbps for 1000 MHz*
- *Integer multiples of 155 Mbps (QPSK) up to 775 Mbps (128QAM) peak rate*
- *64.9% of Shannon capacity achieved*
- *88% of EADR achieved*



QAM Upper Bounded at 256ary

Download vs. Theoretical Upper Bound

- *Peak elevation of 40 degrees*
- *All link parameters are fixed*

Bandwidth (MHz)	Theory Upper Bound (Gbits)	Practical Upper Bound Gbits (%)	Benchmark Gbits (%)	Ad Hoc Variable Rate Gbits (%)
250	619	471 (76.1)	139 (22.5)	424 (68.5)
500	941	834 (88.6)	199 (21.5)	583 (70.0)
1000	1364	934 (68.5)	361 (26.5)	745 (54.6)

Modulation and Coding Strategy

- ***Eb/No performance and waveform are driven by spectrum efficiency***
  - ***Maintain constant modulus signal and constant symbol rate and fully occupy bandpass up to BWE of 2.5 Bps/Hz***
    - ***QPSK, 8PSK***
    - ***Variable rate or shortened FEC codes***
  - ***Shift to QAM for higher capacity for same symbol rate***
- ***FEC coding and decoding***
  - ***R7/8 turbo product code (COTS) with iterated decoding achieves near capacity at manageable complexity***
  - ***Low density product codes with iterated decoding also a strong candidate***

Waveforms

- ***QPSK, 8PSK, m-ary QAM***
- ***Exemplary FEC: Rate 7/8 turbo product code with iterated soft decision decoding***
  - ***128,120 x 128,120 = 14,400 bit data block size***
- ***Symbol rate for 250 MHz BW = 176.4 MHz***
  - ***Excess BW over Nyquist = 1.42***
    - ***Easy fit to bandpass***
    - ***Equalization of realizable filters is straightforward***

Transmitter Configurations

- ***Two strong candidates, data rate determined:***
  - ***TWTA-based design for up to 16QAM***
    - ***Highest power efficiency***
  - ***SSPA-based design for up to 256QAM***

Variable Data Rate CONOPS

- ***Transmitter***
  - *Assuming the use of data packet buffers, read buffers at the desired data rate into distributors and encoder/ modulator strings*
  - *Append or substitute control/sync words*
  - *Synchronize new rate transition with timing epoch*
  - *Timing epochs may coincide with FEC code block and data framing boundaries*
- ***Receiver***
  - *Include matched filter decoding of control/sync words*
  - *Reconfigure receiver filters and decoders for new rate*
  - *Instantiate new rate on received timing epoch*

Earth Terminal Data Rate Control System

- ***Maintain and update LEO orbital elements to forecast track profile***
- ***Estimate rain loss from local rain rate, beacon measurements at rise***
- ***Estimate C/No and set up transmit data rate increments and timing***
- ***Issue rate commands to LEO transmitter***
- ***Anticipate and accommodate rate changes with no loss of receive data continuity***
- ***Check receive SNR and BER to validate rate settings and readapt as needed***
- ***Validate receiver performance against expected performance***
- ***Update control system algorithms as required***

Development of LEO/Network Systems

- *Forward packet recovery algorithms for LEO platforms*
  - *Functional criteria definition*
    - *Interactivity*
    - *Packet loss tolerance*
    - *Latency*
    - *Capacity*
  - *System topology and parameter optimization*
  - *CONOPS and algorithms*
  - *Performance estimation*
- *IP in the platform*
  - *Scientist-user addressing*
  - *Interactive capabilities*
- *Terrestrial network interfacing*
  - *Terrestrial reformats for "standard" network protocols over the NASA network for noninteractive downloads*
  - *IP-like to the user*

Recommended Next Steps

- *Development of specific major rate-variable elements*
- *Development of efficient, high order QAM SSPA-based transmitter*
- *End-to-end system emulation and demonstration*
- *Full and detailed plans and estimates for:*
  - *Supporting development costs*
  - *SWAP for operational system*
  - *Cost schedules and risks for all elements*

Recommended Next Steps (Cont'd)

- *Development of transmitter rate-variable elements*
  - *Modulator/PA control elements*
  - *Mode control implementation*
- *Development of variable word receiver brassboard and demonstration system*
  - *Carrier synchronization*
  - *Soft symbol detection and turbo decoder interface*
- *LEO transmission system emulator*
  - *Variable signal strength*
  - *Doppler emulator*
- *Studies on IP network interface system*
  - *Forward packet recovery algorithms and implementation*
- *Development of end-to-end demonstration system*
  - *System integration and testing*